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# Soil Organic Matter Stratification as an Indicator of Soil Quality in Cropland

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## ABSTRACT

Stratification of soil organic matter pools with soil depth is common in natural ecosystems, as well as when degraded land is restored with conservation tillage. It is hypothesized that the degree of stratification can be used as an indicator of "soil quality", because surface organic matter is essential to erosion control, water infiltration, and conservation of nutrients. Stratification ratios of soil organic C were 1.1, 1.2, and 1.9 under conventional tillage and 3.4, 2.0, and 2.1 under no tillage in Georgia, Texas, and Alberta/British Columbia, respectively. The difference in stratification between conventional and no tillage within an environment was inversely proportional to the standing stock of soil organic C to a depth of 15-20 cm across environments. Greater stratification of soil C and N pools with the adoption of conservation tillage under inherently low soil organic matter conditions (i.e., warmer climatic regime or coarse-textured soil) suggests that standing stock of soil organic matter alone is a poor indication of soil quality. Stratification of biologically active soil C and N pools (i.e., soil microbial biomass and activity) tended to be greater than that of soil organic C under no tillage, but more similar to that of soil organic C under conventional tillage. High stratification ratios of soil C and N pools could be good indicators of soil quality, independent of soil type and climatic regime, because ratios >2 would be uncommon under degraded conditions.

## INTRODUCTION

Soil is an essential natural resource that provides a medium for plant growth, regulates and partitions water flow in the environment, and serves as an environmental buffer in the formation, attenuation, and degradation of natural and xenobiotic compounds (Larson and Pierce, 1991). Management that causes a decline in soil quality reduces these functional abilities, whereas "stewardship" preserves these abilities, and restorative techniques can improve upon them once degraded. The organic contents of soil are vitally important in providing energy, substrates, and the biological diversity necessary to sustain these soil functions. The "soil quality" concept has recognized soil organic matter as an important attribute that has a great deal of control on many of the key soil functions (Doran and Parkin, 1994). However, soil organic matter varies among environments and management systems, generally increasing with higher mean annual precipitation (Burke et al., 1989), with lower mean annual temperature (Jenny, 1980), with higher clay content (Nichols, 1984), with lower grazing intensity (Parton et al., 1987), with higher crop residue inputs and cropping intensity (Franzluebbers et al., 1998), with native vegetation compared with cultivated management (Burke et al., 1989), and with conservation tillage compared with conventional tillage (Rasmussen and Collins, 1991).

A criticism of recent developments in the soil quality concept has been aimed at more clearly defining the role of soil organic matter towards increasing agricultural productivity and environmental quality (Sojka and Upchurch, 1999). They question the "Mollisol-centric" view that soil quality literature has taken and refer readers to a strong correspondence between soil taxonomy and the USDA–Natural Resource Conservation Service's use of soil property data, crop performance, and evaluator perceptions to model and map "a relative index of inherent soil quality" for the USA (Sinclair et al., 1996). Sojka and Upchurch (1999) stressed that regions of the world with low soil organic matter (i.e., Aridisols, Entisols, and Inceptisols) are also highly productive and that total soil organic matter is unreliable as a predictor of soil and crop performance. Obviously, external inputs of irrigation and fertilization contribute much more to productivity in these more typically arid environments than in temperate environments with Mollisols and Alfisols.

Stratification of soil organic matter pools with soil depth is common in many natural ecosystems and managed grasslands and forests, as well as when degraded cropland is restored with conservation tillage. The soil surface is the vital interface that receives much of the fertilizers and pesticides applied to cropland, receives the intense impact of rainfall, and partitions the flux of gases into and out of soil. It is hypothesized that the degree of stratification can be used as an indicator of "soil quality", because surface organic matter is essential to erosion control, water infiltration, and conservation of nutrients. My objectives were to (1) develop this hypothesis, (2) test the capability of several different soil properties to express this stratification hypothesis, and (3) illustrate the potential of soil organic matter stratification to detect management-induced changes in soil quality.

## MATERIALS AND METHODS

Data from several long-term comparisons between conventional tillage (CT) and no tillage (NT) were compiled in this analysis. On a Weswood silty clay loam (fine-silty, mixed, superactive, thermic Udifluventic Ustochrept) in southcentral Texas, soil was collected at depths of 0-5, 5-12.5, and 12.5-20 cm in the tenth year of an experiment comparing tillage (conventional disk and bed and NT), crop sequence [wheat (*Triticum aestivum* L.), wheat/soybean (*Glycine max* (L.) Merr.)-sorghum (*Sorghum bicolor* (L.) Moench), and wheat/soybean], and N fertilization (0 and 68 kg N · $ha^{-1}$). Absolute concentrations of soil properties were reported in Franzluebbers et al. (1994a, b).

In Alberta and British Columbia, soil was collected at depths of 0-5, 5-12.5, and 12.5-20 cm under conventional shallow tillage and NT in small-grain cropping systems at the end of 7 yr on a Donnelly loam (sandy-skeletal, mixed, frigid Typic Eutrocryept), at the end of 16 yr on a Donnelly silt loam, at the end of 4 yr on a Hythe clay loam (fine, montmorillonitic, frigid, Mollic Cryoboralf), and at the end of 6 yr on a Falher clay (fine, montmorillonitic, frigid, Typic Natriboralf). Absolute concentrations of soil properties were reported in Franzluebbers and Arshad (1996a, b, c).

In Georgia, soil was collected at depths of 0-2.5, 2.5-7.5, and 7.5-15 cm under CT, paraplowing with NT planting, shallow cultivation with NT planting, and in-row chisel at planting alternated with NT planting at the end of 4 yr in a millet (*Panicum miliaceum* L.)/clover (*Trifolium incarnatum* L.)-cotton (*Gossypium hirsutum* L.)/rye (*Secale cereale* L.) cropping system. Absolute concentrations of soil properties were reported in Franzluebbers et al. (1999).

Stratification ratios were calculated from soil properties at 0-5 and 12.5-20 cm in Texas and Alberta/British Columbia and from soil properties at 0-2.5 and 7.5-15 cm in Georgia. A complete description of methods employed for soil analyses can be found in original reports. Briefly, soil organic C was determined by the modified Mebius method or dry combustion, particulate organic C was from the dispersed soil not passing a 0.05-mm screen, soil microbial biomass C was determined with the chloroform fumigation-incubation method without subtraction of a control, potential C mineralization was from an aerobic incubation at 25 °C for 24 d, potential N mineralization was from an aerobic incubation at 25 °C for 10 d, the flush of $CO_2$ following rewetting of dried soil was from an aerobic incubation at 25 °C for 3 d, and macroaggregation was the slaked, water-stable fraction of soil retained on sieves with openings of >0.25 mm.

## RESULTS AND DISCUSSION

### Soil organic C under conventional and no tillage in diverse environments

Soil organic C concentration was relatively uniformly distributed within the surface 15-20 cm under long-term CT in Texas and Georgia (Fig. 1). In contrast, NT management resulted in an increase in soil organic C at the soil surface at both of these locations. Accumulation of soil organic C at the soil surface was a result of surface placement of crop residues and a lack of soil disturbance that kept residues isolated from the rest of the soil profile. Greater soil organic C under CT compared with NT at a depth of 7.5-15 cm in Georgia was a result of tillage operations that incorporated surface organic C throughout the profile, including this lower depth. Decomposition of surface-placed residues is often slower than when incorporated in the soil profile (Brown and Dickey, 1970; Ghidey and Alberts, 1993), primarily because of less optimal moisture conditions (Franzluebbers et al., 1996). However, due to the less than optimal decomposition environment under undisturbed, surface placement of residues compared with disturbance and incorporation with tillage, transformation of organic C from plant-derived residues into soil organic C is more effective under NT than under CT (Franzluebbers et al., 1998).

Soil organic C concentration decreased with increasing soil depth under both CT and NT in Alberta/British Columbia (Fig. 1). Unlike in Texas and Georgia, NT did not increase soil organic C at the soil surface compared with CT. The cold, dry climatic conditions and shallow tillage depth (10-15 cm with CT) probably did not offer a significant decomposition advantage to CT over NT, as is often observed in warmer and wetter climates.

Decreasing mean annual temperature increased soil organic C concentration at all soil depths, irrespective of tillage management (Fig. 1). If absolute soil organic C concentration alone were a determinant of soil quality, then CT management could be considered as beneficial as NT in Georgia, because of the same total amount of soil organic C in the 0-15 cm soil profile [2.1 kg · $m^{-2}$ under both management systems (Franzluebbers et al., 1999)]. This same approach would indicate that soil quality in Texas and Georgia, irrespective of tillage management, would be less than half of that in Alberta/British Columbia under CT. However, comparison of absolute amounts of soil organic C among regions does not seem to be an appropriate approach to assessing soil quality, since mean annual temperature and precipitation controls would never allow soil organic C in warmer and drier climates to accumulate to the same level as in cooler and moister climates. To circumvent these environmental limitations, it has been suggested that minimum and maximum values of key soil properties could be established for various climatic regions, in order to develop quantitative relationships between these key soil properties and soil function (Doran and Parkin, 1994). It would be an enormous task to accurately define the minimum and maximum levels of soil properties under the multitude of climatic regions and various other factors such as soil texture, native fertility, soil mineralogy, slope, and aspect, which all control steady-state levels of a soil property, independent of management. Ultimately, land managers need to know the *effect of their management on soil quality*, rather than the effect

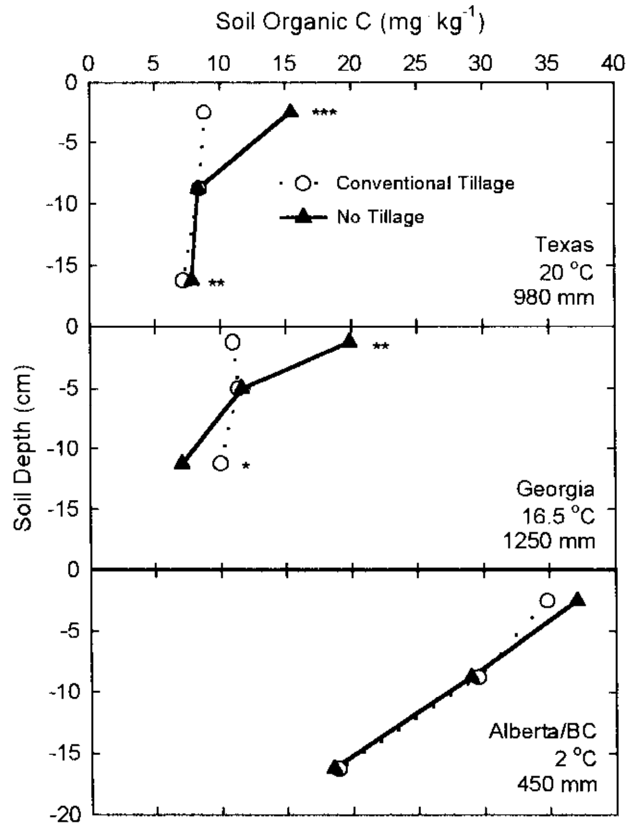


*Figure 1. Soil organic C depth distribution under conventional and no tillage in Texas, Georgia, and Alberta/British Columbia. *, **, and *** indicate significance between tillage management within a depth at P<0.1, P<0.01, and P<0.001, respectively.*

of environmental factors beyond their control. The concept of soil organic matter stratification is offered as an alternative soil quality assessment protocol to overcome inherent differences among environments.

The stratification ratio of soil organic C varied from 1.1 to 1.8 under CT and increased with decreasing mean annual precipitation, decreasing mean annual temperature, and increasing standing stock of soil organic C (Fig. 2). The stratification ratio of soil organic C was greater under NT compared with CT in Georgia and Texas and tended to be greater in Alberta/British Columbia (P=0.11), but the difference between tillage systems decreased with increasing standing stock of soil organic C. Contrary to absolute quantities of soil organic C, the stratification ratio indicated that NT management was improving soil quality the most in Georgia and Texas.

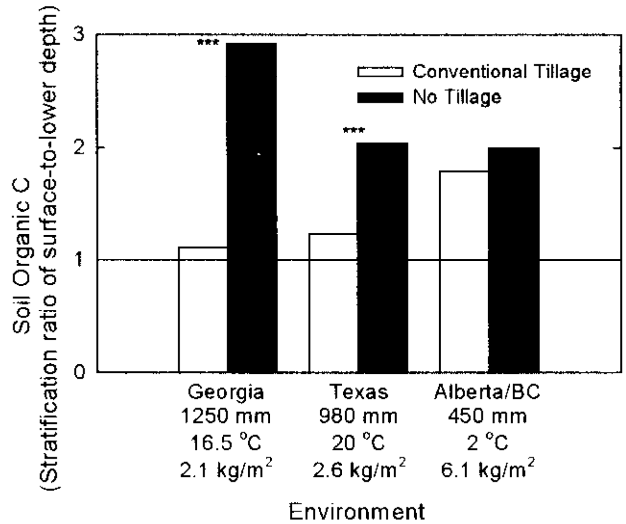


*Figure 2. Stratification ratio of soil organic C under conventional and no tillage in Georgia, Texas, and Alberta/British Columbia. *** indicates significance between tillage management within an environment at P<0.001. Standing stock of soil organic C is to a depth of 15 cm in Georgia and 20 cm in Texas and Alberta/British Columbia.*

Stratification ratios of other commonly measured soil properties in these three environments tended to be similar or slightly higher under CT, but much higher under NT (Table 1). It appears that a number of biologically active soil C and N pools could be equally or more sensitive to changes in stratification with adoption of conservation tillage systems than of total soil organic C alone.

## Stratification ratios of biologically active organic matter pools in Texas

The stratification ratio of potential N mineralization under CT increased from 1.4 to 3.0 with increasing cropping intensity (Fig. 3). This greater ratio with increasing cropping intensity was probably due to greater C inputs with more intensive cropping (Franzluebbers et al., 1998) and reduced soil water available for decomposition by soil

Table 1. Stratification ratios of soil organic C (SOC), soil microbial biomass C (SMBC), basal soil respiration (BSR), potential N mineralization (NMIN), inorganic N (IN), and bulk density (BD) under conventional tillage (CT) and no tillage (NT).

| | TX | | | GA | | | AB/BC | | |
|---|---|---|---|---|---|---|---|---|---|
| Property | CT | | NT | CT | | NT | CT | | NT |
| SOC | 1.2 | *** | 2.0 | 1.1 | *** | 2.9 | 1.8 | | 2.0 |
| SMBC | 1.9 | *** | 3.0 | 1.4 | *** | 3.8 | 1.2 | | 1.2 |
| BSR | 1.9 | | 3.0 | 1.3 | *** | 7.1 | 7.2 | | 6.5 |
| NMIN | 1.9 | * | 3.8 | 1.0 | | 3.6 | 2.6 | ** | 5.7 |
| IN | 1.4 | ** | 2.1 | 0.9 | ** | 2.5 | 2.0 | | 1.9 |
| BD | 0.76 | | 0.77 | 0.88 | ** | 0.62 | 0.76 | | 0.74 |

*, **, and *** indicate significance between tillage management at P<0.1, P<0.01, and P<0.001, respectively.

microorganisms because of greater crop water uptake (Franzluebbers et al., 1995a, b). Greater cropping intensity should lead to increased organic residue returned to soil and greater potential N mineralization. The stratification ratio of potential N mineralization under NT increased from 3.2 to 4.0 with increasing cropping intensity and was significantly greater than under CT in all three cropping systems.

The stratification ratio of soil microbial biomass C under CT was 1.7±0.1 during sampling at planting, flowering, and maturity of wheat (Fig. 4). The stratification ratio of soil microbial biomass C under NT was 3.2±0.2 and significantly greater than under CT during all sampling periods. Seasonal variability in the stratification ratio of soil microbial biomass C was small (3-6%) compared with seasonal variation in absolute estimates of soil microbial biomass C (8-13%) (Franzluebbers et al., 1994b). The low seasonal variability in the stratification ratio of soil microbial biomass C suggests that sampling time would be less critical for soil quality assessment than for obtaining absolute values of soil microbial biomass C.

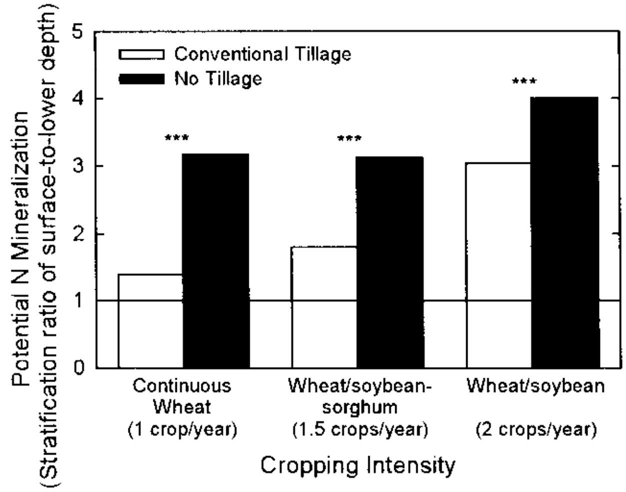


*Figure 3. Stratification ratio (0-5 vs 12.5-20 cm) of potential N mineralization under conventional and no tillage in Texas as affected by cropping intensity. *** indicates significance between tillage management within a cropping sequence at P<0.001.*

## Stratification ratios of biologically active organic matter pools in Georgia

The stratification ratio of the flush of $CO_2$ following rewetting of dried soil increased with decreasing level of soil disturbance (Fig. 5). Conventional tillage, which had inversion tillage each year, had a stratification ratio of 0.9, while in-row chisel, which had no inversion tillage and minimal surface soil disturbance each year, had a stratification ratio of 4.1. The flush of $CO_2$ following rewetting of dried soil is a simple microbial activity assay that requires

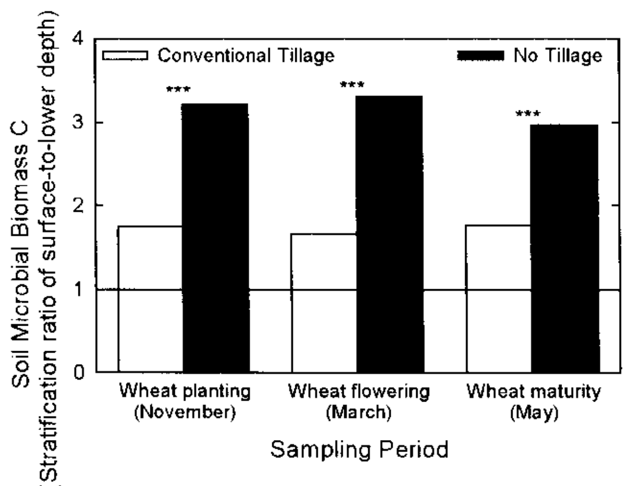


*Figure 4. Stratification ratio (0-5 vs 12.5-20 cm) of soil microbial biomass C under conventional and no tillage in Texas as affected by sampling period. *** indicates significance between tillage management at P<0.001.*

minimal equipment and time and relates well to other biologically active soil organic matter pools, including longer term potential C and N mineralization and soil microbial biomass (Franzluebbers et al., 2000).

The stratification ratio of particulate organic C increased significantly with decreasing frequency of soil disturbance by paraplowing, but was similar with frequency of in-row chiseling (Fig. 6). Particulate organic C is a coarse physical fraction of organic matter that represents an intermediate stage of residue decomposition (Cambardella and Elliott, 1992). Paraplowing is a more disruptive soil management operation than in-row chiseling that likely incorporated some surface residue. This incorporation was expressed well in the stratification ratio of particulate organic C.

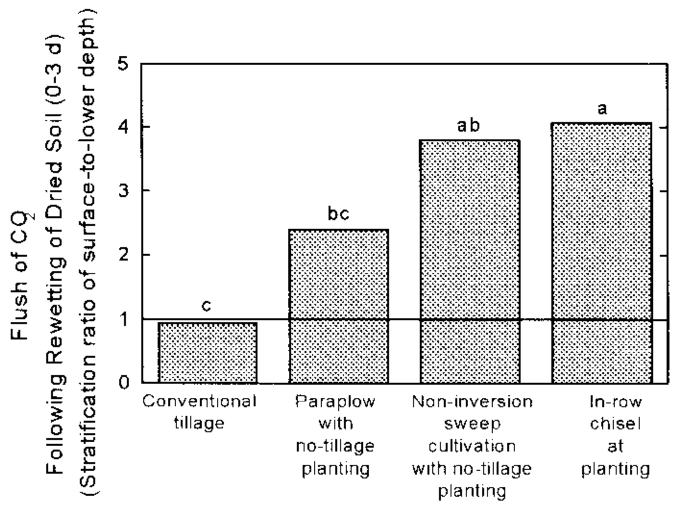


*Figure 5. Stratification ratio (0-2.5 vs 7.5-15 cm) of the flush of $CO_2$ following rewetting of dried soil in Georgia as affected by the type of yearly alternative tillage. Bars with the same letter are not significantly different at $P<0.1$.*

**Stratification ratios of biologically active organic matter pools in Alberta/BC**

The stratification ratio of potential C mineralization averaged across four soils with different textures was unaffected by tillage management, but was greater under NT than under CT in a silt loam and lower in a loam (Fig. 7). Stratification ratios ranged from 4.0 to 8.6, indicating a very high ratio irrespective of tillage management. The high stratification ratios under CT suggest that these soils have not deteriorated greatly with CT as observed in other environments, perhaps because of the cold, dry conditions that are not as conducive to decomposition even under CT. Only in the silt loam, which had the lowest stratification ratio of the four soils

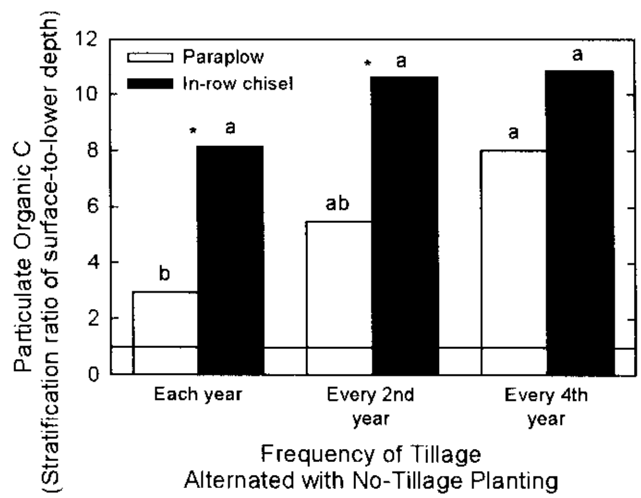


*Figure 6. Stratification ratio (0-2.5 vs 7.5-15 cm) of particulate organic C in Georgia as affected by the frequency of paraplowing and in-row chiseling alternated with no-tillage planting. * indicates significance between tillage management within a frequency at $P<0.1$. Bars within a tillage type with the same letter are not significantly different at $P<0.1$.*

under CT, was there a significant increase due to NT management. This soil was also under CT and NT comparison the longest (i.e., 16 years).

The stratification ratio of macroaggregation was 0.7 in all four soil textural classes under CT (Fig. 8). However under NT management, the stratification ratio of macroaggregation was 0.9 in the two soils with lower clay content and 0.7 in the two soils with higher clay content. The stratification ratio of macroaggregation indicated that coarse-textured soils responded to NT management more than fine-textured soils. This soil textural interaction with tillage management occurred, perhaps because coarse-textured soils are generally lower in the degree of aggregation and organic matter, and therefore, had a greater potential to respond to nondisturbance effects from transient and temporary binding agents (Franzluebbers and Arshad, 1996c). In addition, the stratification ratio of macroaggregation under NT was negatively related to the standing stock of soil organic C to a depth of 20 cm, suggesting that coarse-textured soils inherently low in organic matter responded to NT management the most.

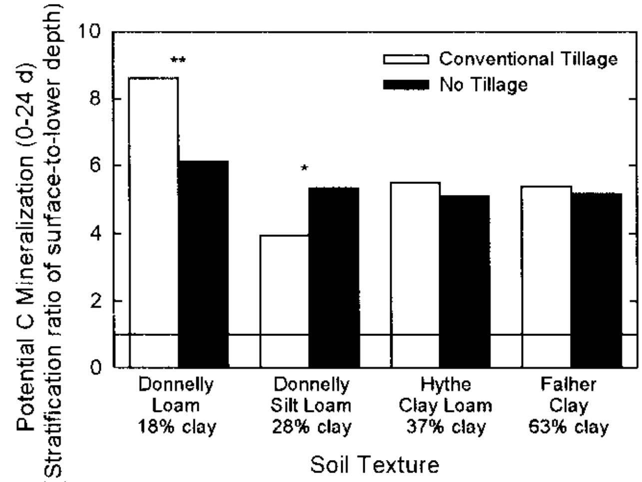


*Figure 7. Stratification ratio (0-5 vs 12.5-20 cm) of potential C mineralization under conventional and no tillage in four soil textural classes in Alberta/British Columbia. * and ** indicate significance between tillage management within a soil texture at P≤0.1 and P≤0.01, respectively.*

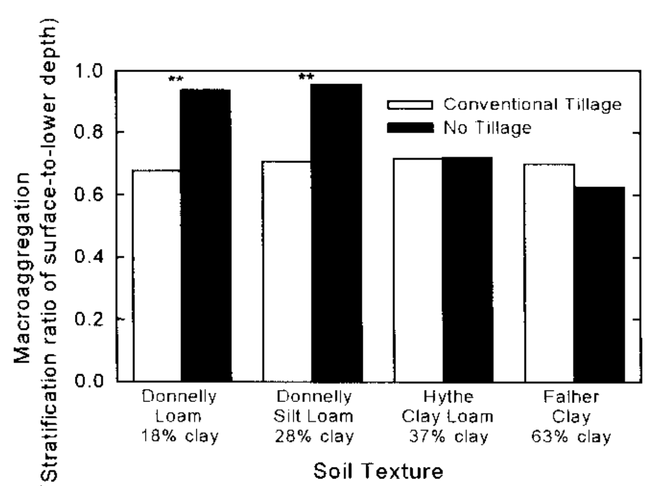


*Figure 8. Stratification ratio (0-5 vs 12.5-20 cm) of macroaggregation under conventional and no tillage in four soil textural classes in Alberta/British Columbia. ** indicates significance between tillage management within a soil texture at P≤0.01.*

## SUMMARY AND CONCLUSIONS

Stratification ratios of most soil properties were greater under NT compared with CT, with the greatest difference between tillage systems occurring in Texas and Georgia (hot, wet, and low soil organic matter environments) and the least difference in Alberta/British Columbia (cold, dry, and high soil organic matter environment). This tillage x environment interaction suggests that conservation tillage management systems may have the most benefit to soil quality in climatic regions and soil conditions with the lowest native soil organic matter. This conclusion supports the criticism of Sojka and Upchurch (1999), which argued that only environments high in soil organic matter have been identified as potentially high in soil quality. The concept of stratification ratio of soil organic matter pools presented here does rely on an increase in soil organic pools, but primarily at the soil surface, because this is the vital interface that receives much of the fertilizers and pesticides applied to cropland, receives the intense impact of rainfall, and partitions the flux of gases into and out of soil. The mechanisms that affect productivity and environmental quality begin at the soil surface.

Stratification ratios of soil organic C and N pools (i.e., total and particulate organic C, soil microbial biomass C, and potential C and N mineralization) under NT management were always >2, while they were often <2 under CT. The exception to this general relationship occurred in soils from Alberta/British Columbia, in which stratification ratios of soil organic C and N pools were also >2 under CT. Because of high 'native' stratification ratios under CT in Alberta/British Columbia, NT management often did not lead to increases in stratification ratios. Certainly more research is needed, but preliminary analyses indicate that stratification ratios of soil organic C and N pools much greater than 2 would be an indication that soil quality was high and the economic and ecological impacts of that particular land management system should be more fully analyzed for its contribution to agricultural sustainability.

Further research is needed to (1) test the applicability of this soil quality indicator approach in different agroecological zones, (2) determine the most appropriate sampling depths for calculating a stratification ratio in diverse environments, and (3) make quantitative relationships between changes in stratification ratios of soil C and N pools and the ability of the soil to function.

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